Geomorphological characteristics of the Passage of Lanzarote (East Canary Islands Region)

Características geomorfológicas del Pasaje de Lanzarote (Región oriental de las Islas Canarias)

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Abstract: The Passage of Lanzarote is an example of a wide oceanic corridor. It extends between the eastern Canary Islands and the Western Africa continental margin. Seafloor morphology of this passage has been analyzed with the aim to know the morphogenetic processes related to both the oceanography and the geology. Multibeam bathymetric data and high and very high resolution seismic profiles obtained in the SUBVENT2 cruise have been used. Five main morphological groups were analyzed: (a) Volcanic or diapiric submarine hills; (b) Tectonic features on the continental slope (linear scarps and a rhomboid-like depression) related to normal faults at the top of buried diapirs; (c) Giant circular depressions initially triggered by submarine venting at the top of diapirs; (d) Sedimentary instabilities and canyons (gullies, canyons, mass transport deposits) that are present specially on the Fuerteventura-Lanzarote ridge must be related to the high energy geological processes, both constructive and dismantling, associated to the evolution of these volcanic domains; and (e) Contouritic features both erosive (central channel, contourite channels) and depositional (mounded and plastered drifts) that occur in the central part of the bottom surface of the passage, and are generated by the interaction of the MW and the interface MW-AAIW with the seafloor.

Keywords: *Morphology, bottom-current interaction, submarine hills, West Africa Margin, Canary Islands*

1. INTRODUCTION

Passages and straits constitute physiographic areas of the oceans where the dynamic of water masses circulation suffers relevant changes. In these areas, an acceleration of the velocity of the water masses should be usually expected due to their channeling and funneling effect. This phenomenon could convert the water masses circulation in a key process controlling the seafloor geomorphology.

The main aim of this work is to define the Passage of Lanzarote (PoL) seabed morphology and to interpret it from their relationship with oceanographic and geological processes. The PoL is a wide oceanic corridor whose physiographic location, together with its oceanographic and geological characteristics, provides exceptional area to analyze the influence of both processes on the seafloor morphology.

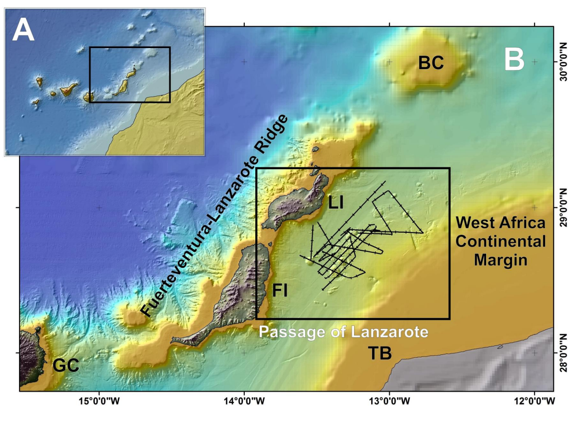

Fig. 1. Location of the Passage of Lanzarote in the Canary Islands Region (A). Study area and navigation map (solid lines) of the SUBVENT-2 cruise (B). BC: Bank of La Concepción; FI: Fuerteventura Island; GC: Gran Canaria Island; LI: Lanzarote Island; TB: Tarfaya Basin.

2. PHYSIOGRAPHY

The Passage of Lanzarote (PoL) corresponds to the Atlantic Ocean region extended between the West Africa continental margin (WACM) to the east and the NE-SW volcanic ridge of Fuerteventura-Lanzarote (FLR) to the west (Fig. 1)**.** On the sea-surface the PoL width varies from 100 km southwards up to 250 km northwards of the FLR. The transversal profile of the PoL bottom surface (Fig. 2) could be described as an asymmetric channel which is narrowing towards the south. The western flank is stepper than the eastern one, and there is a central sector characterized by low gradients between them.

The western flank of the PoL bottom surface corresponds to the FLR. Nowadays, the FLR constitutes a wall of 270 km length that reaches 450 km if we also consider the La Concepcion Bank and the Gran Canaria Island as the northern and southern prolongations respectively of this ridge. The FLR width varies between 8 and 20 km, it is 1200 m high respect to the base of the western flank of the PoL and 3300 m respect to the western side of FLR. It has average slope values of 8°, however the relief of the FLR flanks is clearly more abrupt eastward (up to 40°) than westwards (20° maximum slope). The eastern flank of the PoL is the WACM that displays an arc geometry in plan, its orientation changes from NE-SW trend southwards to ENE-WSW northwards, simultaneously, the width increases (from 45 to 170 km) and the slopes decreases (7° to 1-2°). The distal segment of the margin is characterized by several submarine hills that have been interpreted as diapirs (Acosta *et al.*, 2003). Lastly, the central sector of the seafloor surface of the passage has maximum depths values between 1240 and 1460 m. Its width varies between 20 and 50 km, and shows smooth transversal and longitudinal profiles (0.2-0.5°), although the gradients increase until 15° in relation to local reliefs (submarine hills and depressions).

3. GEOLOGICAL AND OCEANOGRAPHIC SETTING

The PoL results from the elevation of the western boundary, i.e. the FLR, since the Oligocene (Ancoechea *et al.*, 2004) by volcanism. This elevation culminated with the formation of Lanzarote (LI) and Fuerteventura (FI) volcanic islands, dated at 15.5 and 20.6 My respectively (Carracedo *et al.*, 1998). However, the volcanic activity in these islands has continued to historical times (Ancoechea *et al.*, 2004). The eastern boundary of the PoL, i.e. the WACM, corresponds to the offshore prolongation of the Tarfaya basin (TB), which is characterized by salt mobility (Tari *et al.*, 2012).

There are three water masses through the PoL (Fig. 2). (1) The upper thermocline North Atlantic Central Water (NACW), which spans from the surface to the approximate neutral density (Υ_n) value of 27.3 kg m^{-3} (roughly 600m depth) (Hernández-Guerra *et al.*, 2003). NACW shows a mean southward transport of -0.81 Sv, except in autumn that flows northwards (Fraile-Nuez *et al.*, 2010). At intermediate levels, two water masses are interleaved: Antarctic Intermediate Water (AAIW) and Mediterranean Water (MW). (2) AAIW is found below the NACW, mainly between the layers 27.3 and 27.7 kg m^{-3} of neutral density (roughly 600–1100 m depth) with its core centered at 27.6 kg m^{-3} neutral density (roughly 900 m depth). AAIW flows basically northwards with a mean mass transport of +0.09 Sv. (3) The MW reaches deeper than AAIW, roughly from 900m to the bottom of the PoL (Υ_n > 27.45 kg m^{-3}) with a mean southward transport of -0.05 Sv and a similar seasonal pattern of the NACW (Fraile-Nuez *et al.*, 2010).

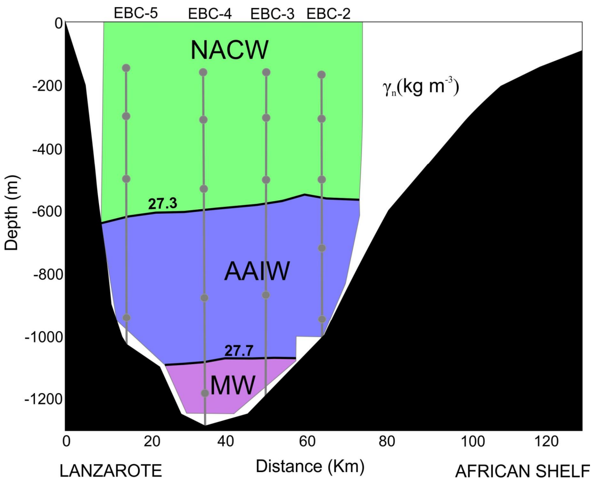

Fig. 2. Distribution of water masses in the PoL using as criteria the neutral density proposed by Hernández-Guerra et al. (2003).

4. MATERIAL AND METHODS

A data-set has been obtained in the SUBVENT2 expedition aboard the R/V Sarmiento de Gamboa (March-April, 2014) including multibeam bathymetry (ATLAS Hydrosweep-DS), very high resolution parametric echosounder (ATLAS Parasound) and high (3 channel airguns) resolution seismic profiles have been used (Fig. 1B). A previous multibeam bathymetric grid (90x90m) from the Instituto Hidrográfico de la Marina (Ministerio de Defensa, Spain) has been also used. These data were acquired by BIO HESPERIDES (EM 12) in the framework of the "Spanish ZEEE programme".

5. MORPHOLOGY

Ten morphological types were identified on the seafloor (Fig. 3):

i) 15 *submarine hills* are located in the PoL between from the south of FI and the north of LI, however the biggest six ones are in front of LI. They show cylindrical or subrounded geometry (2-10.5 km diameter) and elongated and flat shapes at the top (1.2-8.5 km length). Their bases range between 1225 and 1530 m and their tops between 828 and 1336 m water depth. These hills show great irregularities at the top, with minor cones and erosive terraces as the most meaningful features. The cones have 15-70 m height and 350-700 m of diameter. The erosive terraces levels appear around 915-930 m and 1130-1150 m water depth. On the seafloor, towards the ENE of the western hill, there is also a 6 km long ridge of E-W trend and up to 150 m high with singled cones of up to 40 height and 350 m of diameter.

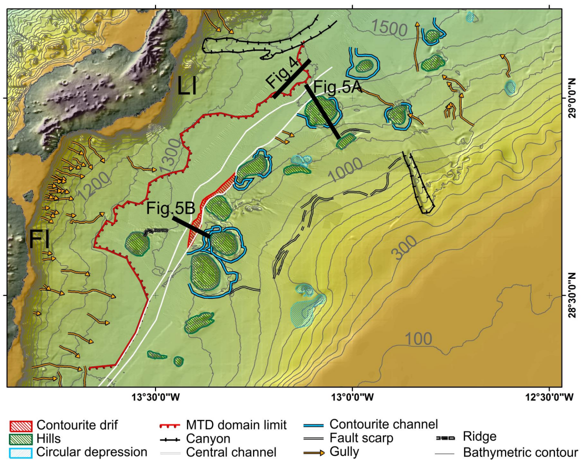

Fig. 3. Main morphologic characteristics of the seafloor of PoL.

ii) Gullies are located in the eastern flank of FLR. They show E-W to NE-SW trends, 1-5km length, and an irregular spatial distribution (Fig. 3).

iii) Two *canyons* have been described (Fig. 3). The first one to the northeast of the FLR with an E-W to NE-SW arc trace, 33 km length, width between 13 km in the headwall and 2.5 km in the slope, and 50 m of incision. The second is located on the WACM, with a strong linear NW-SE direction, 17 km length, 2 km width and 180 m of incision.

iv) Mass transport deposits are present along the FLR lower flank (Fig. 3) as foot of slope fans and debris avalanches in different positions in the stratigraphic record. A recent 20-30 ms thick deposit of debris towards the east of Lanzarote Island has been located (Fig. 4). The slope of the island must be the source area of this deposit.

v) Linear normal faults scarps with 10 km length, up to 20 m deep, with two trend patterns (N-S to NNE-SSW and ENE-SWS to E-W) have been located on the continental slope at 830-950 m water depth (Fig. 3).

vi) A *rhomboid-like depression* is present at 960 m depth on the continental slope. It is 5 km long and 0.8 km width, and is related to normal faults in the same position than the linear scarps (Fig. 3).

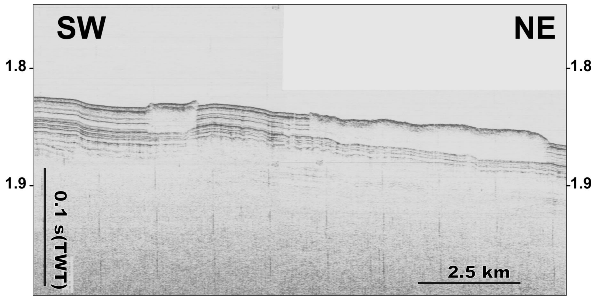

Fig. 4. Mass transport deposits at the base of the western flank of FLR, show location on Fig. 3.

vii) Circular depressions, with a diameter of 2-2.8 km and 90-250 m deep, have been located on the WACM at different depths (Fig. 3). They have asymmetrical profiles and present erosive characteristics (truncated reflectors) on seismic profiles.

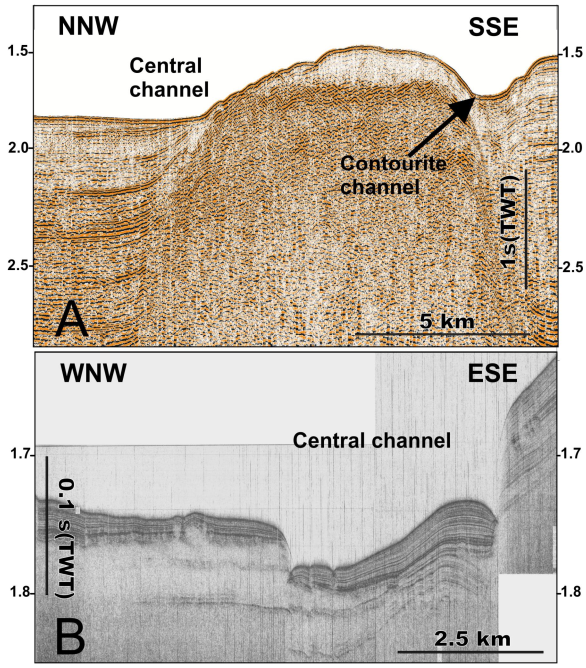

Fig. 6. Along-slope features in the PoL area. A: Seismic reflection profile across a submarine hill in the northern sector of PoL, the smooth erosion associated to the Central channel, and the strong erosive character of the Contouritic channel surrounding the submarine hill. B: Contourite deposits on the Central Channel of Pol in a parametric profile. Show location on Fig. 3.

viii) The *central channel* of the PoL has 100 km length in a NE-SW direction, and its width varies between 1 and 5 km. It is located close to the base of the WACM slope. From 1290 m water depth, the channel deepens toward the NE down to 1460 m and toward the SW down to 1320 m water depth. It shows erosive features on seismic profiles (Fig. 5.A).

ix) Elongated depressions are located around the submarine hills and could be classified as contourite channels. They have quite different lengths (1-17 km) and widths (0.5-2 km), and are constituted by successive coalescence of smaller depressions. They are better developed to the east and south of the submarine hills, and their bases (1270-1530 m water depth) are shallower than the central valley westwards. They show 180 m of incision distributed in successive levels and clear erosive features on seismic profiles (Fig. 6.A). In some cases a terrace level has been located at a depth (~1150 m) which is similar to those levels described on submarine hills.

x) Some minor contourite deposits are distributed along the area; they are *plastered or mounded drifts* NE-SW oriented (Fig. 6.B). They are located between the submarine hills (6-10 km of length) or to the Central channel, respectively. The most important three deposits are situated around 1360-1385 m, 1345-1355 m and 1325-1315 m water depth with a thickness around 50 ms.

6. DISCUSSION AND CONCLUSIONS

The PoL have a great variety of seafloor features that can be grouped into five main groups based on their distinct origin: (a) Submarine hills that have volcanic or diapiric origin and are the most significant features of the central part of the PoL together with contourite channels that border to them. (b) Linear scarps and rhomboid-like depressions are related to normal faults at the top of buried diapirs on the continental slope. They are features tectonically-generated. (c) Giant circular depressions on the continental slope must be initially related to venting (fluid flow emissions) at the top of buried diapirs, but must be later reworked by bottom current dynamics. (d) Canyons, gullies and mass transport deposits at the FLR are related to gravitational instabilities. They are also located on the WACM where they are associated to diapirism. (e) Bottom features related to contourite processes that are mainly produced by erosion processes such as the Central channel and the Contourite channels around submarine hills. Minor scale plastered and mounded drift deposits are present.

The FLR flanks are characterized by down-slope processes constituted by gravitational instabilities that are mainly related to the evolution of volcanic buildings, and by canyons and gullies whose distribution is controlled by the development of high angle slopes. Diapirism and tectonic related structures control the WACM, generating several submarine hills and subcircular depressions, as well as linear scarps, rhomboid-like depressions and some linear canyons. Volcanism is responsible of minor cones edifices on the PoL seafloor and on some of the main hills. One of these hills has been attributed to volcanism in the literature (Acosta *et al.,* 2003).

Lastly, the shallower depth of the PoL seafloor respect to the northern and southern adjacent regions favours the interaction of MW and the AAIW-MW interface with seabed. *Erosive features* in the bottom of the passage are mainly related to along-slope processes and are distributed with NE-SW trends. The Central channel works as a large contourite channel with structural control that favours the funnelling and acceleration of the MW eroding the seafloor (down 1100 m water depth). This process is focused in the base of the slope of the WACM. Similarly, several contourite channels generated around the submarine hills must be related to the intensification of MW. The interaction of the AAIW-MW interface with seafloor (down 900-1100m water depth) and specially surrounding the submarine hills must be produce successive incisions around these features with some characteristic terrace levels. Locally this interface and the co*re of AAIW erode*d the top of the hills around 900m water depth. Down 1400 m depth the interaction of MW is less marked on seafloor.

Acknowledgements

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